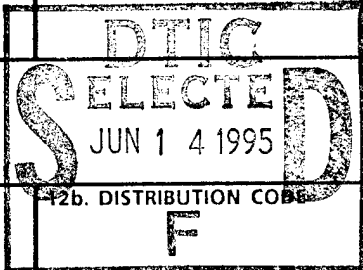


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13. ABSTRACT (Maximum 200 words)

The principal goal of this effort was to develop an improved understanding of the physical and biological environment in the vicinity of isolated seamounts. Field experiments and attendant analyses along with numerical modeling and physical simulations of the region in the vicinity of Fieberling Guyot were conducted. The report findings are divided into three sections: (1) ocean current interactions with isolated topography, (2) jets in rotating and stratified fluids, and (3) other physical modeling experiments.

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**on Time-Dependent Ocean Currents**

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## Summary

This is the final technical report on the project "Laboratory and Numerical Modeling of Topographic Effects on Time-Dependent Ocean Currents" under the Office of Naval Research (ONR) Grant N00014-89-J-1217. The project was the physical modeling component of the ONR Accelerated Research Initiative (ARI) on Flow Over Abrupt Topography. The grant also included support from an Augmentation Award for Science and Engineering Research Training (AASERT).

The ARI's principal goal was the development of an improved understanding of the physical and biological environment in the vicinity of isolated seamounts. In particular field experiments and attendant analyses along with numerical modeling and physical simulations of the region in the vicinity of Fieberling Guyot were conducted. The physical models considered a wide range of problems related to the laboratory simulation of the interaction between ocean current systems and isolated topography. In particular the models included appropriate background stratification and rotation, as well as the unsteady nature of the background currents (e.g., tidal motions). The studies also considered flow past multiple obstacles in order to assess such effects as the critical separation distances for which topographic features could be considered isolated. The unsteady background flows led to the general consideration of flow rectification, the generation of mean currents by unsteady (e.g., periodic) free stream flows or, for turbulent flows, by gradients in the Reynolds shear stresses; these studies were motivated by research under the present grant and are continuing.

The research also examined questions related to the combined baroclinic-barotropic instability of jets in rotating and stratified flows which led to a simulation of the effects of the ocean-floor bathymetry of the Southern Ocean on the path of the Antarctic Circumpolar Current. Finally, numerous other modeling experiments of relevance to physical oceanographic systems were conducted under this grant. These included studies on (i) the efficiency of oscillating (tidal) currents in boundary layer mixing, (ii) the effects of rotation on convective turbulence, (iii) the nature of lens eddies at the interface of a two-layer rotating fluid system, (iv) the characteristics of wakes in stratified flows and (v) turbulent mixing at an inversion layer.

## 1. Overview of Research Findings

This research had a number of complementary long range goals. The first was the development of increasingly realistic physical models of ocean current systems as they pass over and around isolated topography or as they interact with more complex bathymetry. To this end, the comparisons of the models with corresponding analytical and numerical models and with oceanic observations was considered an essential supporting goal.

The research was generally directed toward the development of models applicable to the flow in the vicinity of Fieberling Guyot, the seamount for which field observations for the ONR-ARI on Abrupt Topography were taken. As the project developed, however, new directions of fruitful inquiry were suggested and thus the scope of the investigations broadened beyond that originally envisioned. The overview of the research under this grant is thus divided into three sections corresponding to (i) ocean current interactions with isolated topography, (ii) jets in rotating and stratified fluids, and (iii) other physical modeling experiments.

### 1.1. Ocean Current Interactions with Isolated Topography

The original vision of the modeling to be conducted was to investigate the interaction of a spatially uniform oscillatory current superimposed on a mean free stream with a model of Fieberling Guyot. The modeling was to include the appropriate background stratification and rotation. The pertinent similarity parameters for these studies were the Rossby, temporal Rossby, Ekman and Burger numbers and the topographic height to fluid depth ratio. The fluid depth to topography width ratio is not an important similarity parameter as long as the model experiments are conducted in the parameter ranges for which the model flows are hydrostatic (as are their oceanic counterparts).

These initial studies showed that three characteristic flows might be expected in the vicinity of Fieberling; i.e., fully attached, attached lee-side eddies and eddy shedding. The experiments demonstrated that residence times for fluid parcels advecting past, but above the seamount crest, should be expected to be no greater than about twice the advective time scale (based on the mean free stream speed and the horizontal dimension of the seamount). The experiments also clearly demonstrated that residence times can be substantially larger than the advection scale for fluid parcels passing below the crest and in the immediate lee of the seamount. This phenomenon is associated with the strong return flow in the immediate lee of the topographic feature for both the attached lee-side eddies and eddy shedding regimes.

The modeling experiments also reproduced anticyclonic loops caused by diurnal tides for fluid parcels advecting over the seamount as found by Genin, Noble and Lonsdale (1989). A ubiquitous feature of the studies is a strong anticyclonic mean current in the vicinity of the seamount surface; this result is in good agreement with numerical models; see Boudra

(1989). The experiments also investigated upwelling and downwelling in the vicinity of the seamount. This observable is of fundamental importance to biological oceanographers but is not easily measured in the ocean. The experiments demonstrated that upwelling and downwelling characteristics are strong functions of the particular phase of the diurnal tidal cycle.

Recognizing that Fieberling Guyot might not be isolated dynamically from neighboring seamounts (e.g., Fieberling II Seamount and Hoke Guyot), a series of model studies of a rotating, stratified, time-dependent current impinging on two identical model seamounts of varying separation distance and orientation to the free stream were conducted. The experiments demonstrated the important nature of seamount separation and orientation in establishing various characteristic flows. The general conclusion is that at least in the upper levels of the ocean (say above 1500 m) that Fieberling II Seamount and Hoke Guyot are sufficiently far from Fieberling as to have little influence on the flow field in the vicinity of that topographic feature.

As a result of early field operations in the vicinity of Fieberling, it became apparent that the mean background flow in the region was very weak and that the principal motions near Fieberling were in response to tidal motions and advecting eddy structures. These observations also demonstrated that large vertical and horizontal shears, as well as jet-like motions, were characteristic features of the current system near Fieberling; Roden (1991). The physical modeling program thus began investigating motion systems with weak or no background flow.

An experimental program conducted with the 13 m diameter turntable in Grenoble, France, demonstrated clearly that an oscillatory barotropic motion in the vicinity of an isolated topographic feature drives an anticyclonic mean current above the topography; this current was parameterized in terms of the system parameters to allow extrapolation to oceanic flows. A numerical model employing the quasigeostrophic potential vorticity equation was shown to be in good agreement with the experiments. The laboratory results were also in good agreement with a numerical model of Wright and Loder (1985).

An experimental program concerned with pure oscillatory currents was also conducted for linearly stratified flows in the vicinity of an isolated topography. The experiments were conducted at fixed Burger and Ekman numbers for ranges of the Rossby ( $Ro$ ) and temporal Rossby ( $Ro_t$ ) numbers. Characteristic flow patterns were described and presented on a  $Ro$  against  $Ro_t$  flow regime diagram. Rectified anticyclonic currents were developed for all characteristic flows. Such rectified flows were similar to those observed at Fieberling; see Genin et al. (1989) and Eriksen (1991). The physical modeling experiments demonstrated that for superinertial frequencies (i.e.,  $Ro_t > 1$ ), a resonance phenomenon enhances the strength of the current near the surface, while at subinertial frequencies (i.e.,  $Ro_t < 1$ ), bottom trapping is observed. The laboratory findings support the observations of

Ericksen (1991) near Fieberling Guyot suggesting that superinertial frequencies are more pronounced near the ocean surface.

The studies on oscillating flow-topography interactions led naturally into a more in depth study of the nature of flow rectification in rotating and stratified fluids. One configuration investigated concerned the flow generated near a vertical coast with a flat ocean floor by an alongshore oscillating current. The physical model experiments, supported by numerical model studies, demonstrated that a mean flow is generated near the coast with a direction having the coastline on the right, facing downstream.

Most recently, flow rectification in the vicinity of topographic features has been investigated with the driving flow being shear free turbulence in a homogeneous rotating fluid. The turbulence was generated by vertical oscillations of a circular shaft with O-ring surface roughness elements; the oscillation axis coincided with the axis of symmetry of the circular test cell. In the absence of background rotation, the turbulence is strong in the immediate vicinity of the shaft surface and decays with radial distance  $r$ . It is observed that the turbulence in the oscillatory boundary layer is almost isotropic. When background rotation is present, the turbulence intensity near the shaft is similar to that of the non-rotating experiments. Away from the shaft, in the central portion of the test cell, large-scale mean motions containing cyclonic and anticyclonic vortices are developed owing to small local Rossby numbers. In the vicinity of the shaft, a rectified anticyclonic flow is observed. The flow rectification can be explained using a simple model in which a balance between the Reynolds stress gradients and Coriolis forces induces a mean motion. The magnitude of the rectified flow is found to be proportional to the characteristic turbulent velocity, but independent of the background rotation. This phenomenon may be of substantial importance in the transport of passive scalars in coastal regions where Reynolds stress gradients, owing, for example, to wave breaking along oceanic boundaries, are known to exist.

## 1.2. Jets in Rotating and Stratified Fluids

Jets are ubiquitous features of ocean current systems and thus their study as phenomena themselves or as they interact with topography are important matters in physical oceanography. In the present project, zonal jets with vertical and horizontal shear were established in a circular tank filled with a linearly stratified rotating fluid by withdrawing fluid from the central region of the tank near the free surface and returning the fluid along the tank periphery. The stability characteristics of the jet were investigated as a function of the system parameters. The nature of the combined baroclinic-barotropic instability of the jet was depicted on a Rossby against Richardson number diagram. Such jets can be used to investigate shear flows impinging on isolated topography. Experiments were also conducted to assess the influence of an azimuthal ridge aligned along the jet axis on the stability of the jet. The experiments demonstrated clearly that an along-jet axis ridge tends to stabilize the

jet. It was also demonstrated that the ridge, in the linearly stratified case has less control on stabilizing the motion than corresponding experiments with a two-layer jet.

Laboratory experiments and associated numerical model studies of the interaction of a jet of a homogeneous fluid with an isolated topography of revolution were conducted. These studies demonstrated the importance of the relative vorticity of the background flow approaching the topography. That is, the general flow patterns in the vicinity of the topography are substantially different for cases in which the approach flow is a jet compared with a uniform stream having no relative vorticity. The jets investigated had lateral length scales similar in magnitude to the horizontal scale of the topography. Cases in which the jet axis was to the left, to the right and impinged directly on the topography were investigated. For all cases, the curvature of the transport streamfunction contours was strongly anticyclonic over the topography, with a cyclonic region in the left lee of the feature. The strengths of the cyclonic and anticyclonic motions, however, varied greatly with the orientation of the jet with respect to the topographic feature. Principal differences between the uniform upstream flow case and the jet cases are that (i) when the jet is on the right of the topography, facing downstream, weak cyclones are formed in the left obstacle lee and (ii) transport streamfunction lines in the right obstacle lee exhibit a strong "bulge" caused by the obstacle.

The source-sink driven jet described above was shown to be equivalent to a wind-driven oceanic model jet. Using realistic topography, a model of the Southern Ocean bathymetry on the path of the Antarctic Circumpolar Current (ACC) was developed. This model was in good agreement with oceanic observations of Gordon, Molinelli and Baker (1978). One interesting result was the demonstration of the importance of the Eltanin and Udintsev fracture zones in the vicinity of 135° W on the character of the ACC east of the Drake Passage.

### 1.3. Other Physical Modeling Experiments.

Numberous other physical modeling experiments were at least partially supported under the subject grant. One such study was the completion of a series of experiments and attendant analyses on the effects of rotation on the growth of the convective boundary layer. One interesting aspect of these studies was the observation of laboratory vortices similar in spatial and temporal characteristics to dust devils observed in the desert Southwest.

The grant also supported the completion of a series of laboratory studies on the collapse and evolution of lens eddies in two-layer rotating systems. These results may have some application to better understanding the long-lived behavior of interior oceanic eddy systems.

Motivated by mixing events observed near Fieberling Guyot, experiments concerning the characteristics of mixing in an originally linearly-stratified non-rotating fluid by the oscillation of a vertically oriented right circular cylinder were conducted. The linear density

profile evolves into a non-linear one owing to the non-uniform mixing of the fluid with height caused by the variation in turbulent eddy sizes with depth as forced by the oscillating cylinder. By measuring the rate of increase in potential energy stored in the fluid, it is shown that estimates of the vertical mixing coefficient can be obtained.

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